

MEASUREMENT OF ELASTOMER'S BULK MODULUS BY MEANS OF A CONFINED COMPRESSION TEST

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ABSTRACT

The bulk modulus represents a material's resistance to volume change when subjected to pressure loading. Determination of bulk modulus is important for evaluation of applications where compression is involved. Most methods proposed for this purpose are complicated and costly. A simple method is to compress an elastomer button, fully confined in a metal fixture, on a tensile/compression machine. The reliability of this method is studied and a data-treatment technique is proposed to improve the accuracy. It shows that the testing method, with the new analysis technique recommended, is efficient and can be used as a routine test.

INTRODUCTION

Elastomer products are frequently subjected to compression loading in a variety of uses, such as sealing and mounting applications. It is important to know the elastomer's bulk modulus in order to evaluate its mechanical behavior. It has been common to treat the elastomers as incompressible materials for theoretical convenience.¹ The theoretical results obtained based on the 'incompressibility' assumption can give rise to a significant error if applied for compressive applications.

The bulk modulus is a material constant which defines the material resistance to volume change when subject to compression loading. It can be expressed as²

$$K = p/\epsilon_v, \quad (1)$$

where p and ϵ_v are the hydrostatic pressure and the volumetric strain respectively. For convenience, positive volumetric strain is defined as a decrease in volume. The other material constants, such as Young's modulus E , shear modulus G and Poisson's ratio ν , can be related by²

$$E = 3K(1 - 2\nu), \quad (2)$$

$$E = 2G(1 + \nu), \quad (3)$$

$$\nu = (3K - 2G)/(6K + 2G). \quad (4)$$

Young's modulus can be measured through a tensile test. It is obvious that other material constants can be determined from the above equations as long as two of them are known.

One approach is first to determine Poisson's ratio by measuring the cross-sectional change of a material strip under tension and then to calculate bulk modulus from Poisson's ratio and Young's modulus or shear modulus. This approach is difficult to implement and does not provide a desirable accuracy.

The other approach is to measure bulk modulus directly through experiments. One method is to put a sample in a hydraulic system and then measure the volume change in relation to the system pressure. This method, being complicated and costly, is not suitable for routine testing. It is also difficult to obtain good accuracy due to a variety of factors, such as system leakage, temperature shift, calibration for fluid volume change and surface treatment of the sample.

The simplest method is to compress a sample confined in a metal fixture and to obtain a load-deflection curve. This type of test was used by H. Booth at Rocketdyne in 1962.³ In 1975, Holownia⁴ used a similar method to measure bulk moduli for compounds with various

carbon black contents. For the last three years, this method has been used to measure bulk moduli for various compounds at Parker Seals. This test can be done on a tensile/compression machine, which is available in most mid-sized material laboratories. Although it is easy to carry out, the method is not widely used due to the lack of a careful study of its feasibility and reliability. The purpose of this paper is to study its feasibility as a routine test.

The material constants discussed above are linear constants or constants at infinitesimal strain. Generally, material moduli without further specification are the moduli at infinitesimal strain. The material's resistance to volumetric change actually depends on the volumetric strain or pressure. In other words, bulk modulus is a function of volumetric strain.⁵ In this case, bulk modulus can be expressed as a derivative of a pressure-strain curve, such that

$$K(\epsilon_v) = dp/d\epsilon_v. \quad (5)$$

The derivative-type modulus is not always readily available from experimental results; it is also appropriate to define incremental bulk modulus K_{inc} as

$$K_{inc}^i(\epsilon_v) = \Delta p / \Delta \epsilon_v = (p^{i+1} - p^i) / (\epsilon_v^{i+1} - \epsilon_v^i), \quad (6)$$

where i represents the sequential number of the experimental points. This incremental method is convenient for experimental data treatment and, as it will be shown later, is also useful to minimize testing errors.

EXPERIMENTAL PROCEDURE

EQUIPMENT AND SAMPLE

The Parker Seals 70 durometer silicone compound S604-70 was used for our tests unless otherwise noted. The material was molded into standard ASTM D395 compression set buttons, which are cylindrical buttons measuring approximately 2.79 cm in diameter and 1.27 cm in height. For the sample fit and void study, a button sample was shaved at the circumference in the axial direction as shown in Figure 1. The shaved volume was obtained by weighing the sample before and after the shave. Assuming uniform material density, the change in volume equals the change in weight. The sample for the void study was tested in original, one-side shaved (Figure 1a) and two-side shaved shapes (Figure 1b). The amount shaved at each side was approximately equal.

For the test done on Parker Seals 90 durometer polyurethane compound P4300A90, flat slabs approximately 0.22 cm thick were cut with a circular die and stacked to obtain the size close to that of the regular button samples.

The fixture for bulk modulus testing consisted of top and bottom pieces which were bolted together to confine the button sample, and a piston piece which was used to apply the load to the sample (Figure 2). The fixture top and bottom were designed as separate pieces for easy installation and removal of the rubber sample. All fixture pieces were manufactured from mild steel. The rubber test sample was installed in the circular opening of the top piece and positioned so that the sample was in flush contact with the bottom fixture piece. A piston piece was then placed on top of the button sample. The Instron material testing machine applied the load to the piston to compress the sample and recorded the



FIG. 1.—Sample shapes for volume void study.

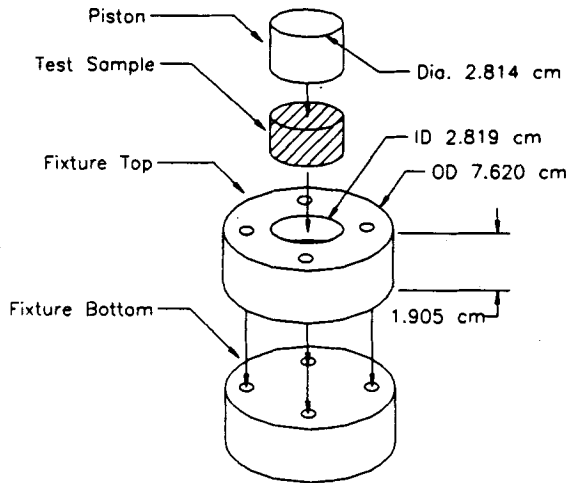


FIG. 2. — Bulk modulus fixture assembly.

amounts of deflection at specified loads. Instron Model 1125 with a Micron I data acquisition module was used for applying the load and obtaining the data. In the unconfined compression test, the sample was compressed between two flat plates with no radial confinement.

GENERAL PROCEDURE

1. Measure thickness of the button.
2. Assemble fixture with sample in place.
3. Apply 220 N pre-load to the sample as a reference starting point.
4. Compress the assembly at the crosshead speed of .127 cm/min.
5. Obtain the Instron machine's crosshead movement at desired loads.
6. Obtain deflections of the sample at specified loads by subtracting the system deflection (deflection of fixture, piston and Instron machine) from the crosshead movement.

NOTES ON EXPERIMENTS

The system deflection is obtained by performing compression test on the piston and fixture without placing any sample inside the fixture. In our experiments, the system deflection accounted for about 1/2 of the total deflection (crosshead movement).

The compression load was assumed to have been applied evenly over the piston's contact surface. Therefore, the pressure applied to the sample was calculated as

$$p = F/A_p, \quad (7)$$

where F is the force exerted on the piston by the Instron machine and A_p is the area of the piston that was in contact with the button sample. Since the diameter of the cylindrical button sample remains constant during the compression, the volumetric strain can be calculated as follows:

$$\epsilon_v = (v_0 - v)/v_0 = (t_0 - t)/t_0, \quad (8)$$

where v is the volume and t is the thickness of the button sample. v_0 and t_0 are the original volume and thickness of the button sample, respectively.

The fit between the piston and the top piece of the fixture had a diametrical clearance of 0.004 cm. The clearance was considered tight enough since material extrusion was not observed with the samples used.

DETERMINATION OF BULK MODULUS

INCREMENTAL METHOD

An ordinary way to determine bulk modulus is to determine the slope of a pressure-volumetric strain curve at small strains. Figure 3 shows the pressure-strain curve for the polyurethane compound. The curve does not pass through the origin due to the sample end-effect,⁴ set-up error and pre-loading. Furthermore, finding the slope from an experimental curve is inefficient, especially when determining the bulk moduli at different strains as is required for nonlinear considerations. In addition, the slope determined from pressure-strain curve is not always accurate, depending on the scatter in experimental points.

In this work, an incremental method is used. First, the incremental bulk modulus is calculated using Equation (6).

$$K_{\text{inc}}^i(\epsilon_v) = \Delta p / \Delta \epsilon_v = (p^{i+1} - p^i) / (\epsilon_v^{i+1} - \epsilon_v^i), \quad (9)$$

The incremental bulk modulus is then plotted versus volumetric strain, as shown in Figure 4 for the polyurethane sample. Due to the set-up error and other factors mentioned, the first point is far away from the curve trend and should be disregarded. Otherwise, the incremental modulus-volumetric strain curve is continuous.

The bulk modulus at infinitesimal strain can be easily obtained by extrapolating the curve to zero strain as shown in Figure 4. The sample end-effect and the set-up error are minimized using the incremental method.

The modulus determined using the incremental method is sufficient for general requirements. For nonlinear considerations, where a high accuracy in agreement between the modulus and the strain is usually required, it is necessary to make a correction to the strain value. To do this find the interception point of the pressure-strain curve and the x-axis as shown in Figure 3 and calculate the true strain by subtracting the x-coordinate of the interception point from the experimental strain value. The volumetric strain shift in Figure 3 is represented in Figure 4.

The bulk modulus so determined for the polyurethane compound is approximately 2950 MPa. Using a hydraulic system, Holownia and James⁶ measured dynamic bulk modulus for a polyurethane compound whose hardness (durometer) was not specified. They found that bulk modulus increases slightly with frequency and varies from about 2700 to 3000 MPa, a range which includes the modulus that is obtained in this work for the 90-durometer compound.

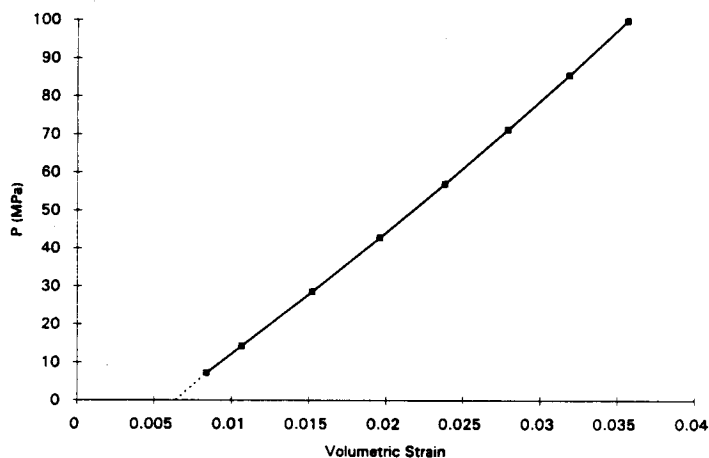


FIG. 3. — Pressure vs. volumetric strain for a polyurethane sample with volumetric strain intercept at 0.0064.

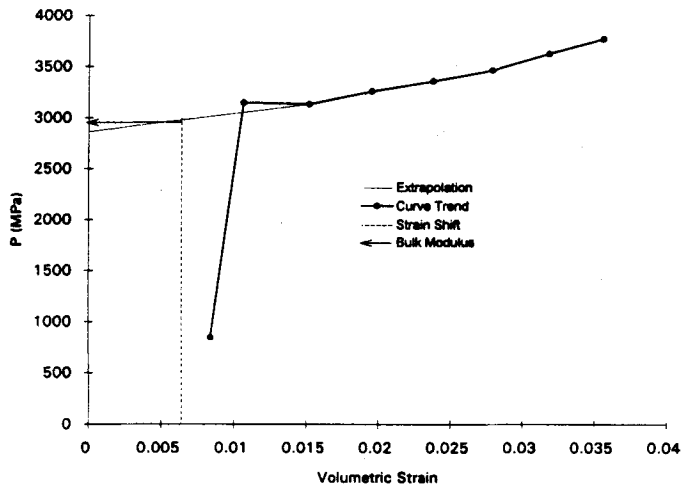


FIG. 4.—Incremental bulk modulus vs. volumetric strain for polyurethane sample.

SAMPLE FIT AND VOIDS

The fit of the sample to the fixture varies from sample to sample. Some samples fit tightly and some fit loosely. The size variation of samples depends on the compound type and sample preparation. For example, samples made of different compounds can have different sizes, even if the same mold is used, due to the differences in their thermal contraction behavior and molding temperature. Sometimes molded samples will have minor defects at the edges or contain interior voids.

To study the effect of sample fit and voids on the bulk modulus determination, compression tests have been conducted for a sample in unshaved, one-side shaved and two-side shaved shapes, as described in the Experimental Procedures Section. The results are graphed in Figure 5. The curve for those shapes with more artificial voids shifted to higher volumetric strain, but the bulk modulus remains approximately the same as those with less artificial

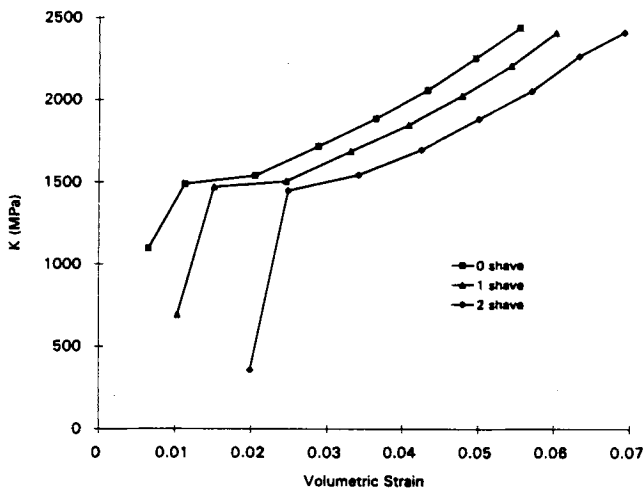


FIG. 5.—Incremental bulk modulus vs. volumetric strain for samples with 0, 1.4 and 2.8% artificial voids.

voids. The strain, for the shape with one-side shaved, shifts approximately 0.6% and it shifts 1.3% for the shape with two-sides shaved. This means that the artificial voids have little effect on the value of the determined bulk modulus. Since the artificial void difference between the samples is much larger than normal variation in sample sizes, sample fit will not appear to pose a problem for bulk modulus determinations.

The results also demonstrate that a correct sample fit is important if a proper nonlinear relation between the bulk modulus and the volumetric strain is required. Samples that fit well provide less strain shifting and thus the bulk modulus curve will be closer to the ideal position.

Samples tested in a confining condition show little relaxation behavior, since repeating tests on a sample give almost the same testing data. This confirms the assumption that the curve shifts are due to the artificial voids.

We can also check the effects of voids by evaluating the difference between the volumetric strain of shaved and unshaved samples. The differences between volumetric strain for the

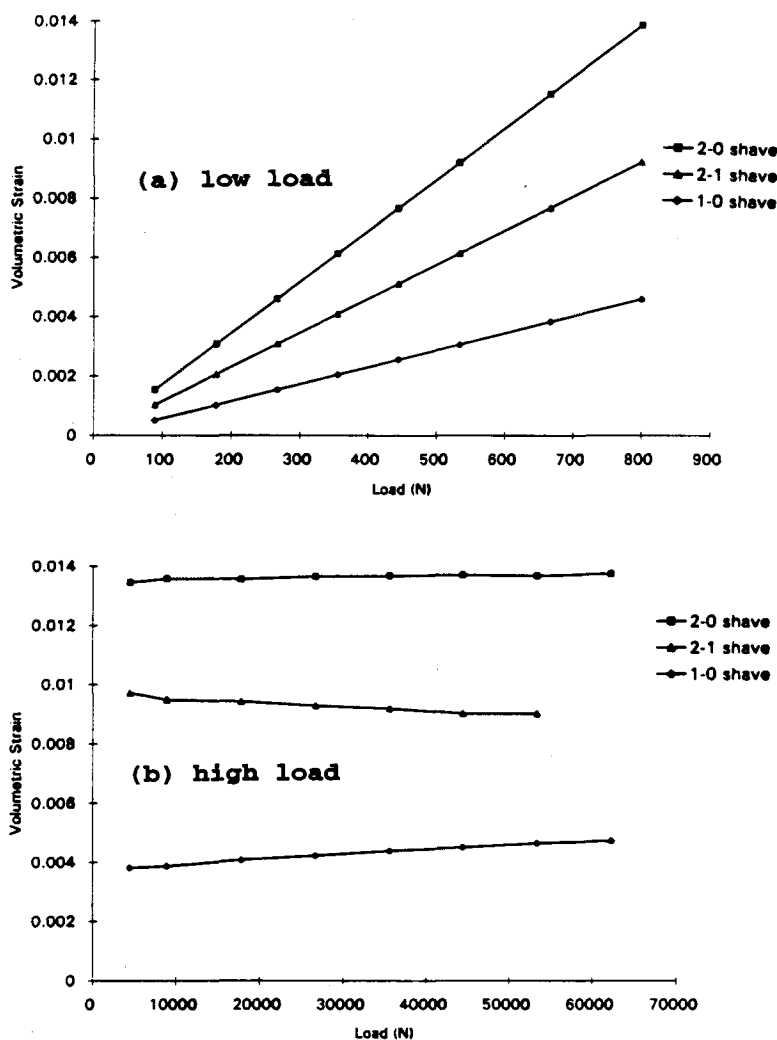


Fig. 6. — Difference between volumetric strains of samples with 0, 1 and 2 sides shaved per Figure 1; (a) low load region; (b) high load region.

shaved and unshaved samples increase linearly until the load reaches 1,000 N (Figure 6a). This indicates that the contribution of the voids to the measured volumetric strain is significant at low volumetric strains. At high loads (>5,000 N) or high volumetric strains, the differences between the volumetric strains of shaved and unshaved sample are almost constant as can be seen in Figure 6b. This is also reflected in the congruency of the curves for the three volume void samples as shown in Figure 5. This indicates that the contribution of the voids to volumetric strain is trivial at high volumetric strain.

OTHER FACTORS

The incremental bulk modulus is determined by the pressure increment Δp and strain increment $\Delta \epsilon_v$ per Equation (4). The load is measured directly from the tensile machine with very high accuracy; the load sensor calibration displays an accuracy with $\pm 0.2\%$. Therefore the reliability of the bulk modulus determined through the proposed method depends on the accuracy in evaluating $\Delta \epsilon_v$ only.

The increment of the total volumetric strain measured, $\Delta \epsilon_v^{\text{total}}$, is a sum of the true (material) strain increment, $\Delta \epsilon_v$, void volumetric ratio increment, $\Delta \epsilon_v^{\text{v0}}$, and other volumetric ratio, $\Delta \epsilon_v^{\text{ot}}$. The increment of the total strain measured $\Delta \epsilon_v^{\text{total}}$ is used as the approximation of the true strain increment $\Delta \epsilon_v$ during the course of this work; *i.e.*,

$$\Delta \epsilon_v \approx \Delta \epsilon_v^{\text{total}}. \quad (10)$$

In reality, they should be related by the following equation

$$\Delta \epsilon_v^{\text{total}} = \Delta \epsilon_v + \Delta \epsilon_v^{\text{v0}} + \Delta \epsilon_v^{\text{ot}}. \quad (11)$$

As discussed in the previous section, the determined bulk modulus value was not significantly affected by the void term $\Delta \epsilon_v^{\text{v0}}$. The term $\Delta \epsilon_v^{\text{ot}}$ includes the possible sample extrusion through the fixture gaps and the fixture deformation. It does not include the contribution of the tensile machine's deflection since it has already been excluded (see Experimental Procedure Section).

The tested samples did not show any flash. It means that sample extrusion is not a concern with the fixture used. The fixture deformation under pressure is simulated using the finite element method. It shows that the fixture volume can have a 0.17% increase when under a pressure of 143 MPa. Volume expansion of the fixture increases almost linearly with the pressure. This results in a 2 to 6% decrease in the bulk modulus values, depending on the magnitude of the material's bulk modulus. This effect can be easily corrected by employing Equation (11).

Another factor to check is the pre-loading effect. Due to the difficulty in determining the contact point or zero volumetric strain point, it is advantageous to set a certain load as a reference during testing. This study uses a 222 N pre-load. Similar to the void effect, this small pre-load will not have much effect on the incremental bulk modulus, but will cause the modulus-strain curve to shift slightly. The amount of the shift depends on the bulk modulus of a sample. For the 90 durometer polyurethane, the strain shift is about 0.0001, and for the 70 durometer silicone compound the shift is about 0.0002. These shifts are trivial compared to the effect of the artificial voids.

The bulk modulus acquired with this method is usually accurate within 10% of the nominal value if the strain is not adjusted, which is accurate enough for most applications. If an application demands higher accuracy, the strain adjustment has to be performed and factored into the bulk modulus determination. This will result in a bulk modulus value that is accurate within 3% of the nominal value.

EFFECT OF LUBRICATION

Holownia's investigation of Poisson's Ratio in 1974 involved lubrication of button samples to avoid partial bonding of the ends.⁴ It was confirmed through correspondence with Dr.

Holownia that the use of different lubricants such as silicone oil or castrol oil did not change his results. The bulk moduli measured in this study were similar, with or without the silicone oil, for the unshaved sample as shown in Figure 7.

The unlubricated experiment was performed on the same samples on three different occasions, with a waiting period of several weeks between the tests. The results were approximately the same each time, which demonstrates repeatability. The samples were lubricated at the bottom end, placed inside the fixture and then lubricated at the end facing the piston. Excess lubrication on the sample surface was eliminated by absorbing it with tissue paper. The silicone oil used was Dow DC 200. The shaved samples, however, presented difficulties in data measurements when lubricants were used. The readings from the Instron machine would not stabilize when testing shaved samples that were lubricated; the pre-load fluctuated as much as 50% even when the crosshead speed was reduced. The fluctuation was not observed for the unshaved sample. This is probably due to the silicone oil filling the artificial voids of the shaved samples. In fact, depending on the amount of lubricants used, oil was forced out of the fixture as the buttons were compressed. Furthermore, the sample size probably affects the data acquisition when the lubricants are added. If samples do not fit tightly in the fixture, oil may be trapped in the gap between the sample and the fixture, thus affecting the recorded data. On the basis of these observations, it is best to use unlubricated samples that fit securely inside the fixture when performing the experiments. Small amounts of lubrication can be used if the samples fit tightly in the fixture; but for samples that do not fit tightly in the fixture, the amount of lubrication used should be minimal to avoid trapping the oil between the fixture and the samples; in the case of loose-fitting samples, the amount of oil used will affect the data measurements.

CONCLUSIONS

A simple method of determining bulk modulus is discussed. This method measures the compression-deflection relationship for a confined material sample on a tensile machine. It shows that the method is reliable and efficient. An incremental data-treatment technique is proposed to minimize testing errors. Factors which affect the accuracy in determining bulk modulus, such as lubrication, sample fit and fixture deformation are analyzed. It shows that this method is suitable for obtaining nonlinear modulus-strain relationships. The simplicity of this testing method makes it feasible as a routine test which can be carried out in most mid-sized material laboratories.

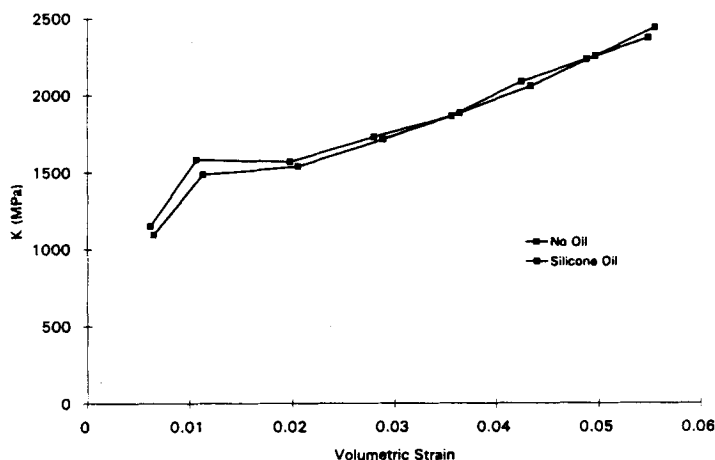


FIG. 7.—Bulk modulus for lubricated (higher modulus at lower volumetric strain) and unlubricated samples.

ACKNOWLEDGMENT

We would like to thank Mr. Robert Barbarin for his informative discussions regarding this topic. The assistance given by Henry Su and John Bajani are acknowledged very much by the authors. Henry Su's work in carrying out much of the testing and data analysis was very important.

REFERENCES

- ¹ Treloar, "The Physics of Rubber Elasticity," Third Edition, Clarendon Press, Oxford, 1975.
- ² Y. C. Fung, "Foundations of Solid Mechanics," Prentice-Hall, New Jersey, 1965.
- ³ "Bulk Modulus of O-Ring Compounds," R & D Laboratory Report DD3382, Parker Seals, Culver City, CA 90232, 1983.
- ⁴ Holownia, *J. Inst. Rubber Ind.* **8**, 157 (1974); *RUBBER CHEM. TECHNOL.* **48**, 246 (1975).
- ⁵ W. Ogden, "Non-Linear Elastic Deformations," Ellis Horwood Limited, New York, 1984.
- ⁶ P. Holownia, *RUBBER CHEM. TECHNOL.* **66**, 749 (1993).

[Paper No. 2, presented at the Spring ACS Rubber Division Meeting (Chicago), May 19-22, 1994;
revised Jul. 22, 1994]